Observation of the Semileptonic Decays $B \to D^*\tau^-\overline{\nu}_\tau$ and Evidence for $B \to D\tau^-\overline{\nu}_\tau$

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We present measurements of the semileptonic decays $B^- \rightarrow D^0\tau^-\overline{\nu}_\tau$, $B^- \rightarrow D^{*0}\tau^-\overline{\nu}_\tau$, $\overline{B}^0 \rightarrow D^+\tau^-\overline{\nu}_\tau$, and $\overline{B}^0 \rightarrow D^{*+}\tau^-\overline{\nu}_\tau$, which are potentially sensitive to non–Standard Model amplitudes. The data sample comprises 232×10^6 $\Upsilon(4S) \rightarrow B\overline{B}$ decays collected with the *BABAR* detector. From a combined fit to B^- and $\overline{B}^0$ channels, we obtain the branching fractions $\mathcal{B}(B \rightarrow D\tau^-\overline{\nu}_\tau) =$

$(0.86 \pm 0.24 \pm 0.11 \pm 0.06)\%$ and $\mathcal{B}(B \to D^* \tau^- \overline{\nu}_\tau) = (1.62 \pm 0.31 \pm 0.10 \pm 0.05)\%$ (normalized for the $\overline{B}^0$), where the uncertainties are statistical, systematic, and normalization-mode-related.

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Semileptonic decays of B mesons to the τ lepton—the heaviest of the three charged leptons—provide a new source of information on Standard Model (SM) processes [1, 2, 3], as well as a new window on physics beyond the SM [4, 5, 6, 7, 8]. In the SM, semileptonic decays occur at tree level and are mediated by the W boson, but the large mass of the τ lepton provides sensitivity to additional amplitudes, such as those mediated by a charged Higgs boson. Experimentally, $b \to c\tau^-\overline{\nu}_\tau$ decays [9] are challenging because the final state contains not just one, but two or three neutrinos as a result of the τ decay.

Branching fractions for semileptonic B decays to τ leptons are predicted to be smaller than those for $\ell = e,\ \mu$ [10]. Calculations based on the SM predict $\mathcal{B}(\overline{B}^0 \to D^+\tau^-\overline{\nu}_\tau) = (0.69 \pm 0.04)\%$ and $\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau) = (1.41 \pm 0.07)\%$ [8], which account for most of the predicted inclusive rate $\mathcal{B}(B \to X_c\tau^-\overline{\nu}_\tau) = (2.30 \pm 0.25)\%$ [2] (here, X_c represents all hadronic final states from the $b \to c$ transition). Calculations [4, 5, 6, 7, 8] in multi-Higgs doublet models show that substantial departures, either positive or negative, from the SM decay rate could occur for $\mathcal{B}(B \to D\tau^-\overline{\nu}_\tau)$. Those for $\mathcal{B}(B \to D^*\tau^-\overline{\nu}_\tau)$, however, are expected to be smaller.

Theoretical predictions for semileptonic decays to exclusive final states require knowledge of the form factors, which parametrize the hadronic current as functions of $q^2 = (p_B - p_{D^{(*)}})^2$. For light leptons ($e$, μ), there is effectively one form factor for $B \to D\ell^-\overline{\nu}_\ell$, while there are three for $B \to D^*\ell^-\overline{\nu}_\ell$. If a τ lepton is produced instead, one additional form factor enters in each mode. The form factors for $B \to D^{(*)}\ell^-\overline{\nu}_\ell$ decays involving the light leptons have been measured [11]. Heavy quark symmetry (HQS) relations [12] allow one to express the two additional form factors for $B \to D^{(*)}\tau^-\overline{\nu}_\tau$ in terms of the form factors measurable from decays with the light leptons. With sufficient data, one could probe the additional form factors and test the HQS relations.

The first measurements of semileptonic b-hadron decays to τ leptons were performed by the LEP experiments [13] operating at the Z^0 resonance, yielding an average [14] inclusive branching fraction $\mathcal{B}(b_{\text{had}} \to X\tau^-\overline{\nu}_\tau) = (2.48 \pm 0.26)\%$, where b_{had} represents the mixture of b-hadrons produced in $Z^0 \to b\bar{b}$ decays. The Belle experiment has recently obtained $\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau) = (2.02^{+0.40}_{-0.37} \pm 0.37)\%$ [15].

We determine the branching fractions of four exclusive decay modes: $B^- \to D^0\tau^-\overline{\nu}_\tau$, $B^- \to D^{*0}\tau^-\overline{\nu}_\tau$, $\overline{B}^0 \to D^+\tau^-\overline{\nu}_\tau$, and $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$, each of which is measured relative to the corresponding e and μ modes. To reconstruct the τ, we use the decays $\tau^- \to e^-\overline{\nu}_e\nu_\tau$ and $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$, which are experimentally most accessible. The main challenge of the measurement is to separate $B \to D^{(*)}\tau^-\overline{\nu}_\tau$ decays, which have three neutrinos, from $B \to D^{(*)}\ell^-\overline{\nu}_\ell$ decays, which have the same observable final-state particles but only one neutrino.

We analyze data collected with the *BABAR* detector [16] at the PEP-II e^+e^- storage rings at the Stanford Linear Accelerator Center. The data sample used comprises 208.9 fb^{-1} of integrated luminosity recorded on the $\Upsilon(4S)$ resonance, yielding 232×10^6 $B\overline{B}$ decays.

The analysis strategy is to reconstruct the decays of both B mesons in the $\Upsilon(4S) \to B\overline{B}$ event, providing powerful constraints on unobserved particles. One B meson, denoted B_{tag}, is fully reconstructed in a purely hadronic decay chain. The remaining charged particles and photons are required to be consistent with the products of a $b \to c$ semileptonic B decay: a hadronic system, a $D^{(*)}$ meson, and a lepton (e or μ). The lepton may be either primary or from $\tau^- \to \ell^-\overline{\nu}_\ell\nu_\tau$. We calculate the missing four-momentum $p_{\text{miss}} = [p_{e^+e^-} - p_{\text{tag}} - p_{D^{(*)}} - p_\ell]$ of any particles recoiling against the observed $B_{\text{tag}} + D^{(*)}\ell$ system. A large peak at zero in $m^2_{\text{miss}} = p^2_{\text{miss}}$ corresponds to semileptonic decays with one neutrino, whereas signal events form a broad tail out to $m^2_{\text{miss}} \sim 8\ (\text{GeV}/c^2)^2$. To separate signal and background events, we perform a fit to the joint distribution of m^2_{miss} and the lepton momentum ($|\mathbf{p}^*_\ell|$) in the rest frame of the B meson. In signal events, the observed lepton is the daughter of the τ and typically has a soft spectrum; for most background events, this lepton typically has higher momentum.

We reconstruct B_{tag} candidates [17] in 1114 final states $B_{\text{tag}} \to D^{(*)}Y^\pm$. Tag-side $D^{(*)}$ candidates are reconstructed in 21 decay chains, and the $Y^\pm$ system may consist of up to six light hadrons ($\pi^\pm$, π^0, $K^\pm$, or K^0_S). B_{tag} candidates are identified using two kinematic variables, $m_{\text{ES}} = \sqrt{s/4 - |\mathbf{p}_{\text{tag}}|^2}$ and $\Delta E = E_{\text{tag}} - \sqrt{s}/2$, where $\sqrt{s}$ is the total e^+e^- energy, $|\mathbf{p}_{\text{tag}}|$ is the magnitude of the B_{tag} momentum, and E_{tag} is the B_{tag} energy, all defined in the e^+e^- center-of-mass frame. We require $m_{\text{ES}} > 5.27\ \text{GeV}/c^2$ and $|\Delta E| < 72$ MeV, corresponding to $\pm 4\sigma$ (standard deviations). We reconstruct B_{tag} candidates in approximately 0.3% to 0.5% of $B\overline{B}$ events.

For the B meson decaying semileptonically, we reconstruct $D^{(*)}$ candidates in the modes $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, $K^0_S\pi^+\pi^-$; $D^+ \to K^-\pi^+\pi^+$, $K^-\pi^+\pi^+\pi^0$, $K^0_S\pi^+$, $K^-K^+\pi^+$; $D^{*0} \to D^0\pi^0$, $D^0\gamma$; and $D^{*+} \to D^0\pi^+$, $D^+\pi^0$. D (D^*) candidates are selected within 4σ of the D mass ($D^* - D$ mass difference), with σ typically 5–10 MeV/c^2 (1–2 MeV/c^2). Electron candidates must have lab-frame momentum $|\mathbf{p}_e| > 300\,\text{MeV}/c$; muon candidates must have an appropriate signature in the muon detector system, effectively requiring $|\mathbf{p}_\mu| \gtrsim 600\,\mathrm{MeV}/c$. The energy of electron candidates is corrected for bremsstrahlung energy loss if photons are found close to the electron direction.

We require that all charged tracks be associated with either the $B_{\rm tag}$, $D^{(*)}$, or ℓ candidate. We compute $E_{\rm extra}$, the sum of the energies of all photon candidates not associated with the $B_{\rm tag} + D^{(*)}\ell$ candidate system, and we require $E_{\rm extra} < 150$–300 MeV, depending on the $D^{(*)}$ channel. We suppress hadronic events and combinatorial backgrounds by requiring $|\mathbf{p}_{\rm miss}| > 200$ MeV/c and $q^2 > 4$ (GeV/c^2)^2. If multiple candidate systems pass this selection, we select the one with the lowest value of $E_{\rm extra}$. To improve the $m^2_{\rm miss}$ resolution, we perform a kinematic fit to the event, constraining particle masses to known values and requiring tracks from B, D, and K^0_S mesons to originate from appropriate common vertices. All event selection requirements and fit procedures have been defined using simulated events or using control samples in data that exclude the signal region.

Figure 1 shows the distributions of $m^2_{\rm miss}$ for the four $D^{(*)}\ell$ channels, along with the projections of the maximum likelihood fit discussed below. We observe large peaks at $m^2_{\rm miss} \approx 0$ as well as events in the signal region at large $m^2_{\rm miss}$. The peaks are mainly due to $B \to D^{(*)}\ell^-\overline{\nu}_\ell$, which serve as normalization modes. The structure of this background is shown in the inset figures, which expand the region $-0.4 < m^2_{\rm miss} < 1.4$ (GeV/c^2)^2. $B \to D^*\ell^-\overline{\nu}_\ell$ background is the dominant feature in the two $D^*\ell$ channels (Figs. 1a, c); the two $D\ell$ channels (Figs. 1b, d) are dominated by $B \to D\ell^-\overline{\nu}_\ell$ decays but also include substantial contributions from true D^* mesons where the low-momentum π^0 or photon from $D^* \to D\pi^0$ or $D\gamma$ is not reconstructed. Similarly, $B \to D^*\tau^-\overline{\nu}_\tau$ events can feed down to the $D\ell$ channels. The fit therefore includes feed-down components for both the signal and normalization modes, as well as smaller feed-up contributions from $B \to D(\ell^-/\tau^-)\overline{\nu}$ into the $D^*\ell$ channels. Other sources of background include $B \to D^{**}(\ell^-/\tau^-)\overline{\nu}$ events (here D^{**} represents charm resonances heavier than the $D^*(2010)$, as well as non-resonant $D^{(*)}n\pi$ systems with $n \geq 1$); charge-crossfeed ($B \to D^{(*)}\ell^-\overline{\nu}_\ell$ events reconstructed with the wrong charge for the $B_{\rm tag}$ and $D^{(*)}$ meson, typically because a low-momentum $\pi^\pm$ is swapped between them); and combinatorial background. This last background is dominated by hadronic B decays, such as $B \to D^{(*)}D_s^{(*)}$, that produce a secondary lepton, including τ leptons from D_s decay.

To constrain $B \to D^{**}(\ell^-/\tau^-)\overline{\nu}$ background, we select four control samples, identical to the signal channels but in which an extra π^0 meson is observed. Most of the D^{**} background in the signal channels occurs when the π^0 from $D^{**} \to D^{(*)}\pi^0$ is not reconstructed, so these control samples provide a normalization of the background source. D^{**} decays in which a $\pi^\pm$ is lost do not have the correct charge correlation between the $B_{\rm tag}$ and $D^{(*)}$, and decays with two missing charged pions are rare. The feed-down probabilities for the $D^{**}(\ell^-/\tau^-)\overline{\nu}$ background are determined from simulation, with uncertainties in the D^{**} content treated as a systematic error.

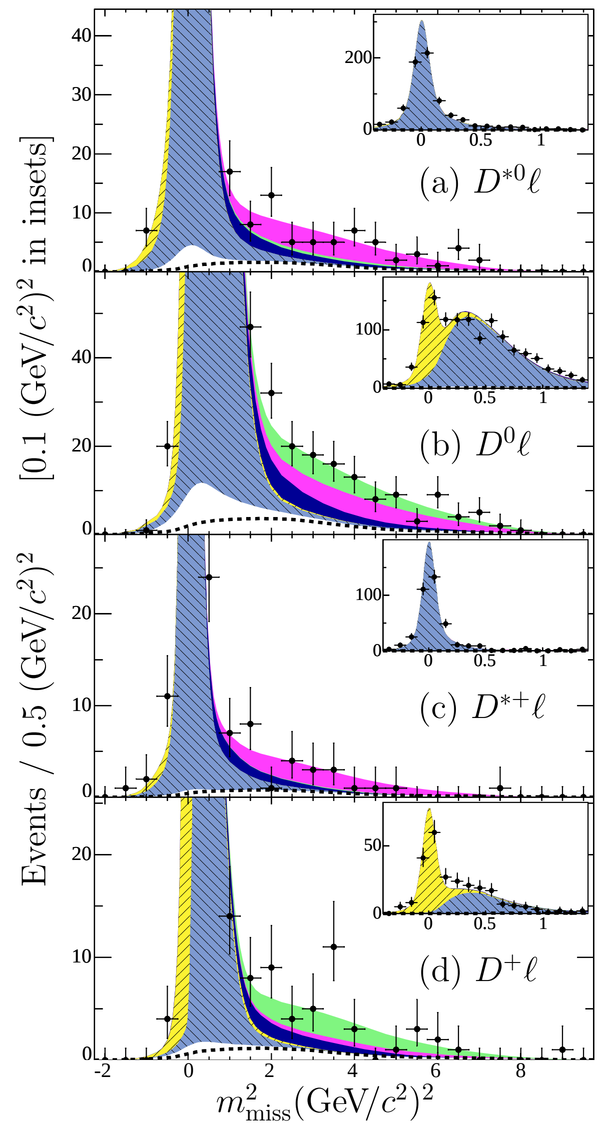

FIG. 1: (Color online) Distributions of events and fit projections in $m^2_{\rm miss}$ for the four final states: $D^{*0}\ell^-$, $D^0\ell^-$, $D^{*+}\ell^-$, and $D^+\ell^-$. The normalization region $m^2_{\rm miss} \approx 0$ is shown with finer binning in the insets. The fit components are combinatorial background (white, below dashed line), charge crossfeed background (white, above dashed line), the $B \to D\ell^-\overline{\nu}_\ell$ normalization mode (// hatching, yellow), the $B \to D^*\ell^-\overline{\nu}_\ell$ normalization mode (\\ hatching, light blue), $B \to D^{**}\ell^-\overline{\nu}_\ell$ background (dark, or blue), the $B \to D\tau^-\overline{\nu}_\tau$ signal (light grey, green), and the $B \to D^*\tau^-\overline{\nu}_\tau$ signal (medium grey, magenta). The fit shown incorporates the B^-–$\overline{B}^0$ constraints.

We perform a relative measurement, extracting both signal $B \to D^{(*)}\tau^-\overline{\nu}_\tau$ and normalization $B \to D^{(*)}\ell^-\overline{\nu}_\ell$ yields from the fit to obtain the four branching ratios $R(D^0)$, $R(D^+)$, $R(D^{*0})$, and $R(D^{*+})$, where, for example, $R(D^{*0}) \equiv \mathcal{B}(B^- \to D^{*0}\tau^-\overline{\nu}_\tau)/\mathcal{B}(B^- \to D^{*0}\ell^-\overline{\nu}_\ell)$. These ratios are normalized such that ℓ represents only one of e or μ; however, both light lepton species are included in the measurement. Signal and background yields are extracted using an extended, unbinned maximum likelihood fit to the joint ($m^2_{\rm miss}$, $|\mathbf{p}^*_\ell|$) distribution. The 18-parameter fit is performed simultaneously in the four signal channels and the four D^{**} control samples. In each of the four signal channels, we describe the data as the sum of seven components (shown in Fig. 1): $D\tau^-\overline{\nu}_\tau$, $D^*\tau^-\overline{\nu}_\tau$, $D\ell^-\overline{\nu}_\ell$, $D^*\ell^-\overline{\nu}_\ell$, $D^{**}(\ell^-/\tau^-)\overline{\nu}$, charge crossfeed, and combinatorial background. The four D^{**} control samples are described as the sum of five components: $D^{**}(\ell^-/\tau^-)\overline{\nu}$, $D\ell^-\overline{\nu}_\ell$, $D^*\ell^-\overline{\nu}_\ell$, charge crossfeed, and combinatorial background. Probability distribution functions (PDFs) are primarily determined from simulated event samples. Both the signal and normalization modes are described using HQET-based form factors [18] for which the parameters and their uncertainties are determined by experimental measurements [11]. Parameters describing the amount of the dominant feed-down components—D^* feed-down into the D channels—are determined directly by the fit.

Table I summarizes the results from two fits, one in which all four signal yields can vary independently, and a second fit in which we constrain [19] $R(D^+) = R(D^0)$ and $R(D^{*+}) = R(D^{*0})$. The $m^2_{\rm miss}$ projections shown in Fig. 1 are those from this B^-–$\overline{B}^0$-constrained fit.

The features of the event sample have been extensively checked. The observed lepton spectra are well described by the fit both in signal- and in background-dominated regions. The properties of reconstructed $B_{\rm tag}$ mesons, such as charged and neutral daughter multiplicities, are consistent with expectations. Control samples of $B \to D^{(*)}\ell^-\overline{\nu}_\ell$ events, kinematically selected without a cut on $m^2_{\rm miss}$, provide checks of numerous distributions, including the $m^2_{\rm miss}$ tails.

Systematic uncertainties on R associated with the fit, $(\Delta R/R)_{\rm fit}$ in Table I, are determined by running ensembles of fits in which input parameters are distributed according to our knowledge of the underlying source, and include the PDF parametrization (2% to 12%); the composition of combinatorial backgrounds (2% to 11%); the mixture of D^{**} states in $B \to D^{**}\ell^-\overline{\nu}_\ell$ decays (0.3% to 6%); the $B \to D^*$ form factors (0.2% to 1.9%); the π^0 reconstruction efficiency, which affects the D^* and D^{**} feed-down rates (0.5% to 1.1%); and the $m^2_{\rm miss}$ resolution for $B \to D^*\ell^-\overline{\nu}_\ell$ events (0.1% to 1.6%). Uncertainties on the $B \to D$ form factors contribute less than 1%. Uncertainties on R propagated from the ratio of efficiencies, $(\Delta R/R)_\varepsilon$ in Table I, are typically small due to cancellations, and include the limited statistics in the simulation (0.8% to 1.5%) and systematic errors related to detector performance (0.2% to 0.7%). Uncertainties from modeling final-state radiation are 0.3% to 0.5%; uncertainties on the branching fractions of the reconstructed modes contribute 0.3% or less. Finally, the uncertainty on $\mathcal{B}(\tau^- \to \ell^-\overline{\nu}_\ell\nu_\tau)$ [14] contributes 0.2% to all modes.

Table I gives the significances of the signal yields. The statistical significance is determined from $\sqrt{2\Delta(\ln\mathcal{L})}$, where $\Delta(\ln\mathcal{L})$ is the change in log-likelihood between the nominal fit and the no-signal hypothesis. The total significance is determined by including $(\Delta R/R)_{\rm fit}$ in quadrature with the statistical error.

We have presented measurements of the decays $B \to D\tau^-\overline{\nu}_\tau$ and $B \to D^*\tau^-\overline{\nu}_\tau$, relative to the corresponding decays to light leptons. We find $R(D) = (41.6 \pm 11.7 \pm 5.2)\%$ and $R(D^*) = (29.7 \pm 5.6 \pm 1.8)\%$, where the first error is statistical and the second is systematic. Normalizing to known $\overline{B}^0$ branching fractions [20], we obtain

$$\begin{aligned}\mathcal{B}(B \to D\tau^-\overline{\nu}_\tau) &= (0.86 \pm 0.24 \pm 0.11 \pm 0.06)\% \\ \mathcal{B}(B \to D^*\tau^-\overline{\nu}_\tau) &= (1.62 \pm 0.31 \pm 0.10 \pm 0.05)\%,\end{aligned}$$

where the third error is from that on the normalization mode branching fraction. The significances of the signals are 3.6σ and 6.2σ, respectively. The modes $B^- \to D^0\tau^-\overline{\nu}_\tau$, $B^- \to D^{*0}\tau^-\overline{\nu}_\tau$, and $\overline{B}^0 \to D^+\tau^-\overline{\nu}_\tau$ have not been studied previously, while the measurement of $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ is consistent with the Belle result [15]. The averaged branching fractions are about 1σ higher than the SM predictions but, given the uncertainties, there is still room for a sizeable non-SM contribution.

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TABLE I: Results from fits to data: the signal yield ($N_{\rm sig}$), the yield of normalization $B \to D^{(*)}\ell^-\overline{\nu}_\ell$ events ($N_{\rm norm}$), the ratio of signal and normalization mode efficiencies ($\varepsilon_{\rm sig}/\varepsilon_{\rm norm}$), the relative systematic error due to the fit yields ($(\Delta R/R)_{\rm fit}$), the relative systematic error due to the efficiency ratios ($(\Delta R/R)_\varepsilon$), the branching fraction relative to the normalization mode (R), the absolute branching fraction ($\mathcal{B}$), and the total and statistical signal significances ($\sigma_{\rm tot}$ and $\sigma_{\rm stat}$). The first two errors on R and $\mathcal{B}$ are statistical and systematic, respectively; the third error on $\mathcal{B}$ represents the uncertainty on the normalization mode [20]. The last two rows show the results of the fit with the B^-–$\overline{B}^0$ constraint applied, where $\mathcal{B}$ is expressed for the $\overline{B}^0$. The statistical correlation between $R(D)$ and $R(D^*)$ in this fit is -0.51.

Mode	$N_{\rm sig}$	$N_{\rm norm}$	$\varepsilon_{\rm sig}/\varepsilon_{\rm norm}$	$(\Delta R/R)_{\rm fit}$ [%]	$(\Delta R/R)_\varepsilon$ [%]	R [%]	$\mathcal{B}$ [%]	$\sigma_{\rm tot}$ ($\sigma_{\rm stat}$)
$B^- \to D^0\tau^-\overline{\nu}_\tau$	35.6±19.4	347.9±23.1	1.85	15.5	1.6	31.4±17.0±4.9	0.67±0.37±0.11±0.07	1.8 (1.8)
$B^- \to D^{*0}\tau^-\overline{\nu}_\tau$	92.2±19.6	1629.9±63.6	0.99	9.7	1.5	34.6± 7.3±3.4	2.25±0.48±0.22±0.17	5.3 (5.8)
$\overline{B}^0 \to D^+\tau^-\overline{\nu}_\tau$	23.3±7.8	150.2±13.3	1.83	13.9	1.8	48.9±16.5±6.9	1.04±0.35±0.15±0.10	3.3 (3.6)
$\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$	15.5±7.2	482.3±25.5	0.91	3.6	1.4	20.7± 9.5±0.8	1.11±0.51±0.04±0.04	2.7 (2.7)
$B \to D\tau^-\overline{\nu}_\tau$	66.9±18.9	497.8±26.4	—	12.4	1.4	41.6±11.7±5.2	0.86±0.24±0.11±0.06	3.6 (4.0)
$B \to D^*\tau^-\overline{\nu}_\tau$	101.4±19.1	2111.5±68.1	—	5.8	1.3	29.7± 5.6±1.8	1.62±0.31±0.10±0.05	6.2 (6.5)

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